CTE Tailored Materials
for
Hybrid Mirror Systems

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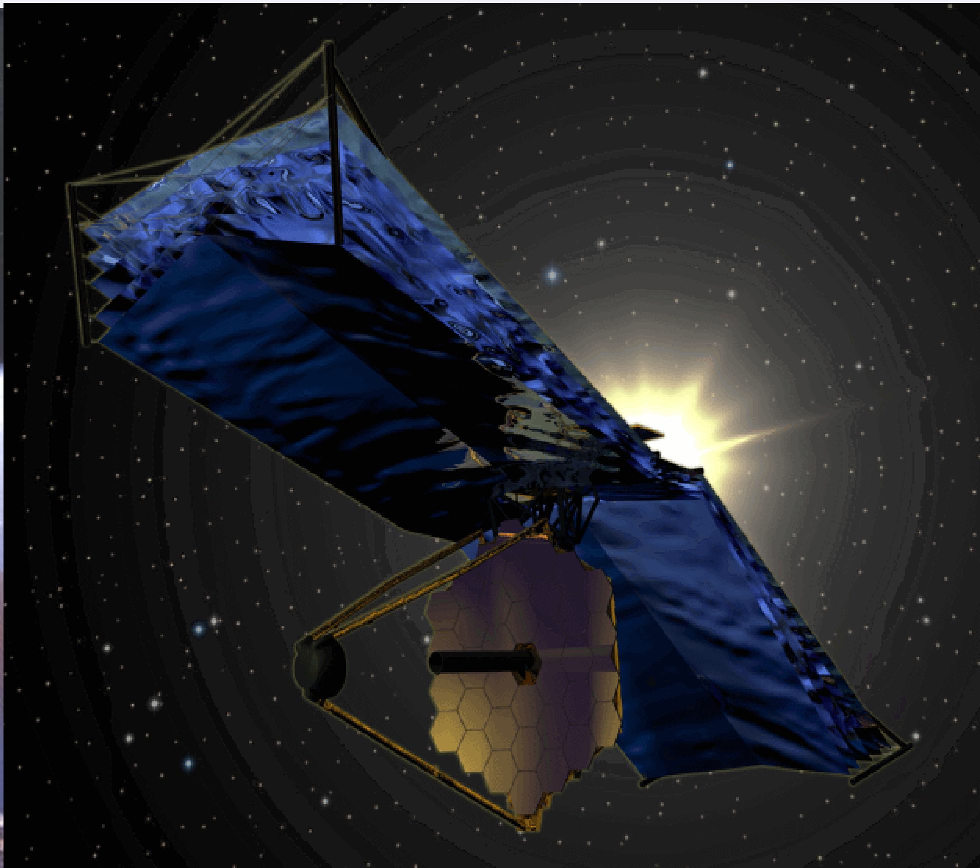
Directed Energy

Surveillance

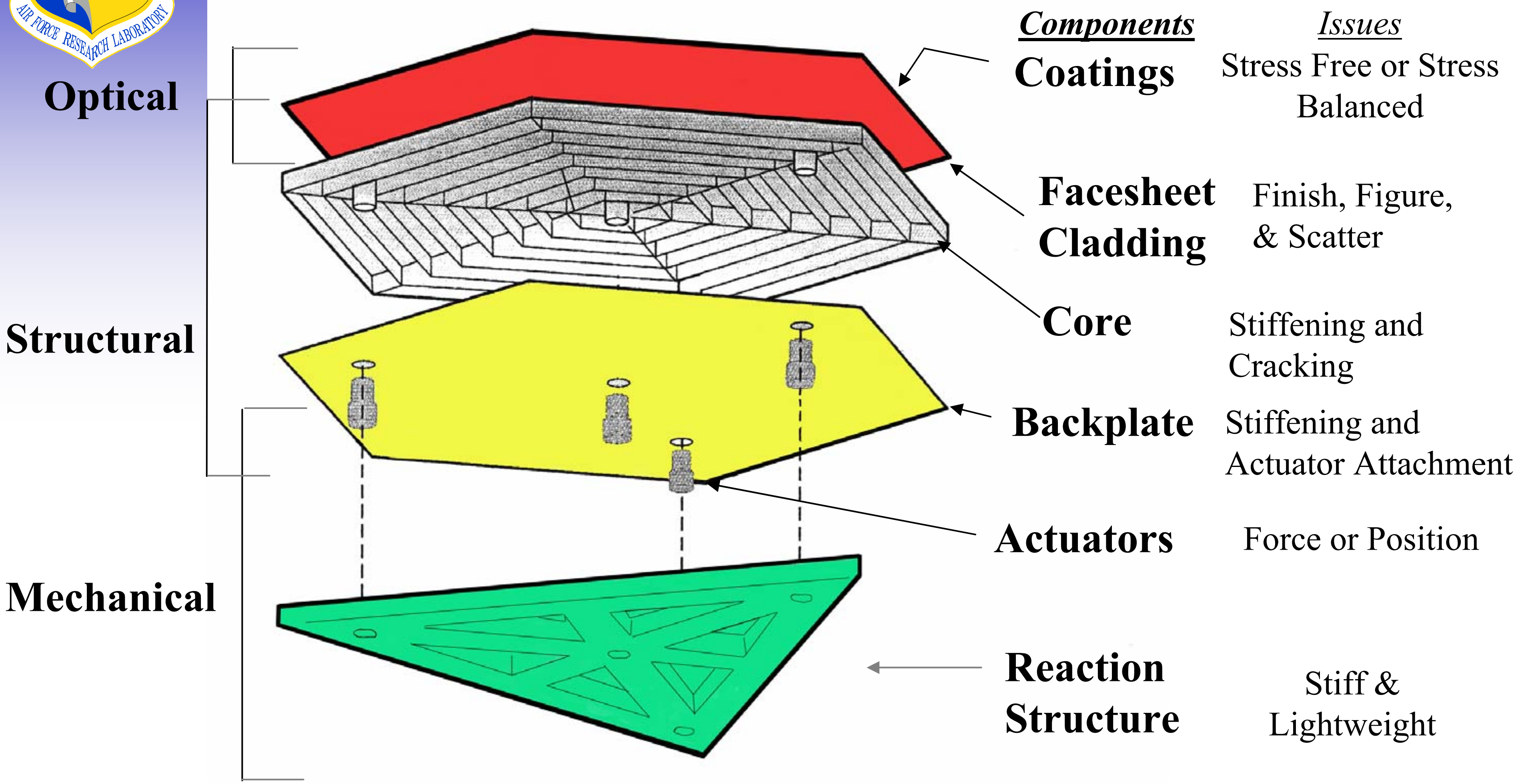


Requirements Depend on System Needs

- Areal Density: AMSD (<15 kg/m^2), DLM, ABL/Directed Energy (33-70 kg/m^2)
- Surface Figure: < λ/20 (Low Spatial Frequency Error)
- Surface Finish/Roughness: < 10 nm (High Spatial Frequency Error); < 2 nm of DE systems
- Frequency: Depends ABL (PM: >400 Hz)
- Production Times: AMSD (Goal: < 2 years); SBIRs (Now 300 days, Goal: 60 days); ABL(Now: years, Goal: months)
- Production Rates: DLM, SBL (> 200 m^2/yr); World Production Rate 50 m^2/yr
- Radius of Curvature Matching: Deployable Optics (5 meters +/- 2%, with ROC Matching < 40 micron difference between segments)
- Size: SBIRS (< 50 cm), ABL (1.5 m), JWST (6 m), SBL (15m), LDO (25m)
- Thermal: ABL (Ambient Air), SBL(Ambient Space), SBIRS-Low (Cryo)

Focused on Increasing Performance in Areal Density/Lightweight, Durability, Production Time, & Production Rates

Schematic of Lightweighted Linear Actuated Mirror



Stability Requires CTE Matching Between Components

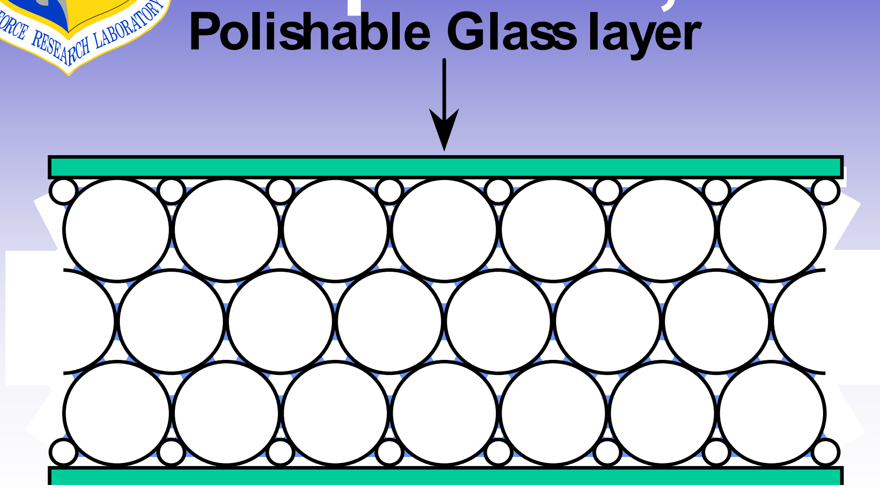
CTE Tailorability in Glass

Alloying to Increase Openness	Precipitation of – CTE Crystals
SiO_2 + 7% TiO_2	Li_2O + Al_2O_3 +SiO_2 (LAS)
Vapor Grown [Corning/ULE]	Melt Grown [Schott/Zerodur]

Properties:	Density (ρ)	Young's Modulus (E)	CTE @ RT (α)	RT Thermal Conductivity (k)	RT Fast Fracture Tensile Strength	RT Fracture Toughness	Hardness Knoop	Typical Surface Finish
Units:	$Kg/m^3 \times 10^{-3}$	GPa	ppm / K	W/m K	MPa	$MPa\text{-}m^{-0.5}$	kg/mm2	Å
mirror #1 DESIRED:	**LOW**	**HIGH**	**LOW**	**HIGH**	**HIGH**	**HIGH**	**LOW**	**LOW**
Pyrex (Corning)	2.23	60.00	3.20				472	
Fused Silica	2.20	73.00	0.55	1.50		0.77	475	
ULE (Corning)	2.20	67.00	0.02	1.30	100	1.8		1 to 2
Zerodur (Schott)	2.53	91.00	0.05	1.67	110	0.9		2
C/Pyrex Composite Disc.	2.00	168.00	0.10	20.00	600	22	470	1000

Problems: Non-homogeneous Dispersion, Segregation, and Coarsening

Zero CTE Glass Sol's, Foams, Spheres, Balloons & Arrays



- AFRL/ML **DUS&T Program**– MSNW Inc. shall produce the glass materials needed for constructing zero CTE glass microsphere and microballoon arrays.

-Glass microsphere arrays will minimize quilting distortions and eliminate continuous crack paths along joints as seen in web-facesheet designs.

- Microspheres and microballoons can be used as fillers in PMC mirror substrates.

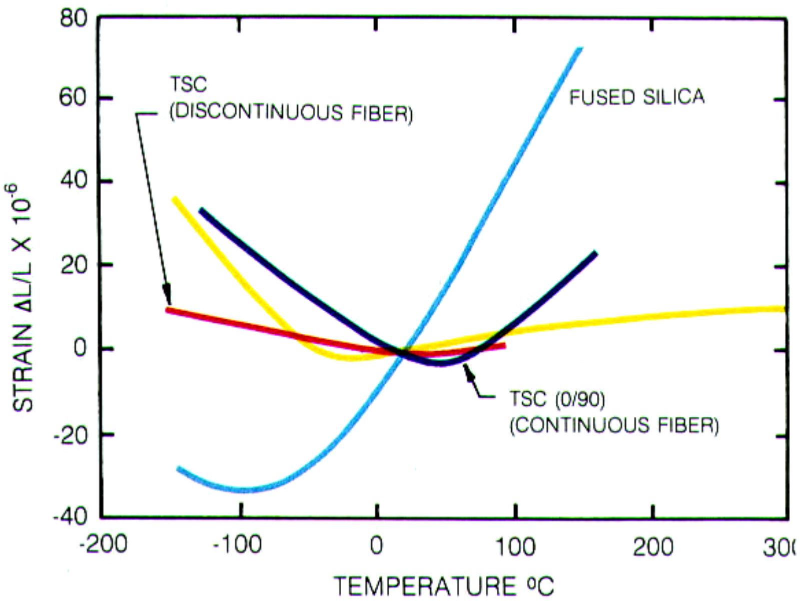
- **Phase I (funded)** – Produce zero CTE sols by <u>**Solution Alloying {similar to ULE}**</u>. Then fabricate bonding agents, coatings, microspheres, microballoons, and arrays.

  - Obtain mechanical properties as a function of geometry & density for glass arrays.

Phase II (not funded) To design, fabricate and test a 0.5m array mirror

C_{fiber} /Glass Composite Mirrors

UTRC's "Compglas" Mirrors



• In the 1980's UTRC produced carbon fiber reinforced glass [C_f/ Glass] in both continuous and discontinuous forms.

•The CTE of the material was tailored to near zero values.

•The density was reduced and the strength, modulus, and fracture toughness were drastically increased.

•Unfortunately, these structural substrates could only be polished to 1000A finish and zero CTE Sol-Gel cladding wasn't available.

	Glass	[C_f/ Glass]
α	3.2	0.1
ρ	2.2	2.0
σ	100	600
E	67	168
K_1C	1	22

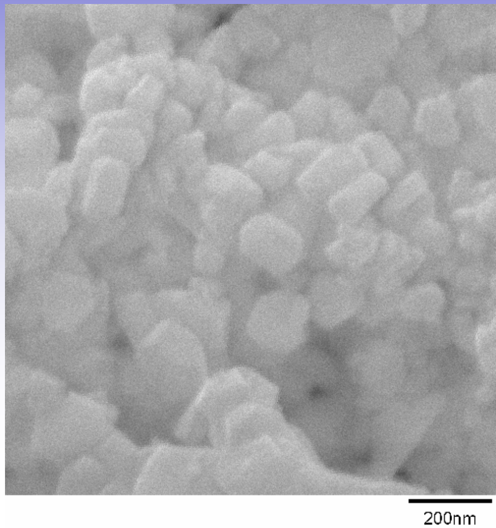
Negative CTE, Nano-Disperiods for CTE Tailorability

AFRL/ML + NRO funding supported government and on-site contractor (UES Inc.) personnel to investigate **Particulate Alloying** {similar to Zerodur but without over-aging issues}

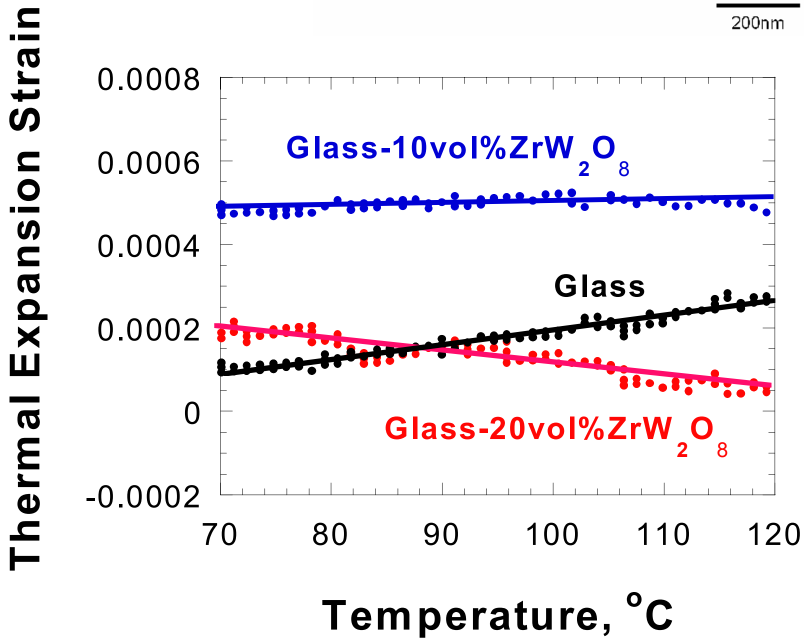
•Develop cubic, negative CTE compound such as ZrW_2O_8 that can be used as dispersiod to tailor the CTE of glass, foams, aero gels, ceramics, metals, and polymers (organic and inorganic).

•Investigate the production of nano sized powders for uniform dispersions and if needed surface activation for good bonding to a matrix.

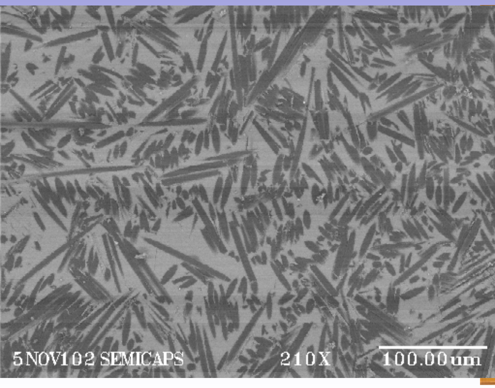
•**Status** - Successfully produced single phase nano sized ZrW_2O_8 powders. Currently scaling up the process to produce quart sized quantities from a single batch.

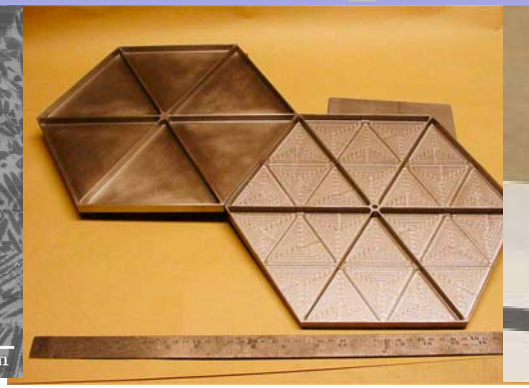


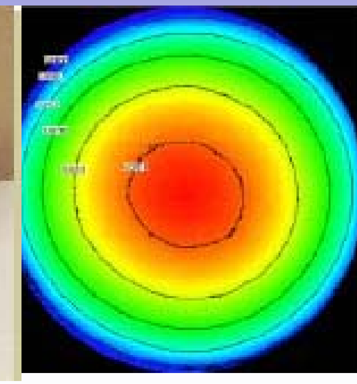
Soft agglomerates of 100nm ZrW_2O_8 powders



Graphite Fiber Reinforced Magnesium and Aluminum Alloys for Space Mirrors





SBIR Program Goals: Develop C_{fiber}/Aluminum and C_{fiber}/Magnesium composite manufacturing technology to produce lightweight mirrors.

Plan: **Phase I (completed) -**Near net-shape casting using discontinuous fiber mats, fast machining to final shape, deposit Si and polish to final figure.

Phase II (on going) - Joining of segments to make large mirror substrates. Investigate claddings and replication technology using either nano laminates and/or polymer imprint. Mechanical & physical property testing. Optical characterization.

Phase I (negotiation) - Phase I-Near net-shape casting using continuous fiber weaves to increase stiffness, machining to final shape, deposit Si and polish to figure.

Payoff: Very high specific strength, stiffness, and fracture toughness. Easy fast machining will saving time and cost. Replication could eliminate polishing cost.

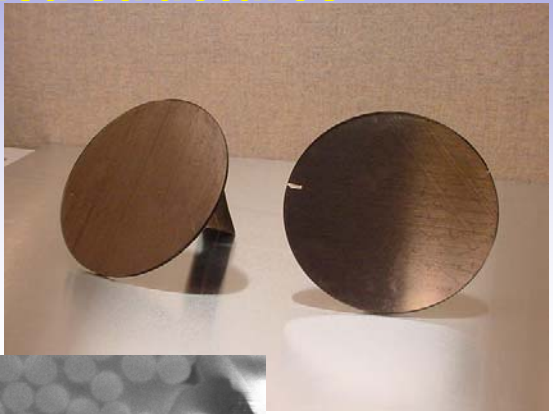
Siliconized - SiC/SiC and C/SiC Composite Mirror

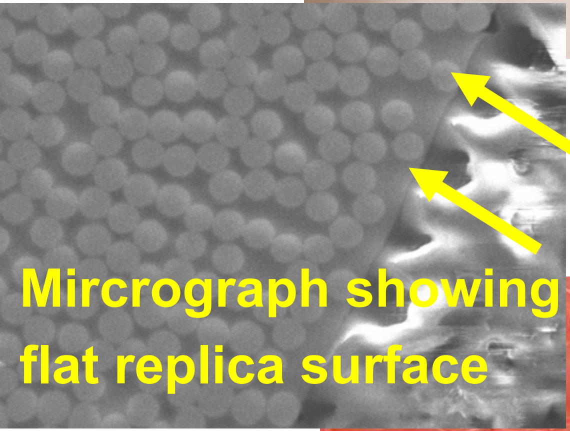
- Ceracom is a spinoff company of Trition Systems.
- They produced small, partially dense, continuous reinforced SiC/SiC and C/SiC CMC's mirror preforms by Chemical Vapor Infiltration [CVI].
- Melt infiltrated the preform with Silicon to densify as well as replicate the mirror surface.
- Fine polished to obtain the desired surface finish.
- They observed no fiber print-through or figure instability under thermal cycling conditions from RT to 227ºC.

Si-SiC/SiC CMC mirror from Ceracom (2inch)

Carbon$_{fiber}$/Polymer Matrix Composite Replica Mirrors

Replica structures





Mircrograph showing flat replica surface

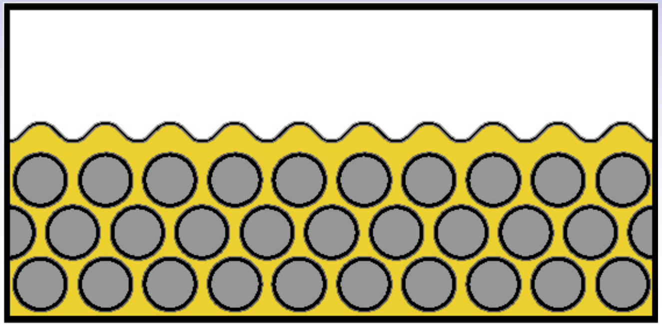
Flat replica surface and mandrel

- **AFRL IR&D**:
  - Achieve optical surface quality of carbon-fiber mirror replica structures with resin-rich layer or bonded nano-laminate.
  - Marry replica to carbon foam or isogrid composite for high quality, high stiffness, and fast manufacture.
- **Program Plan:**
  - Investigate fiber print through and roughness of facesheet based on composite material.
  - Eventually investigate surface figure and roughness of nano-laminate bonded to carbon-fiber structure.

Carbon-Fiber Composites

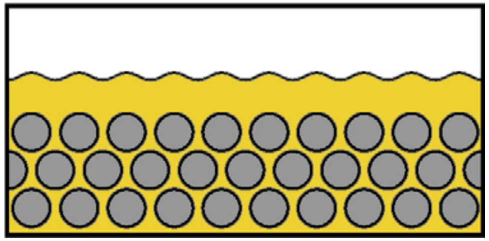
Fiber Print Through Issue

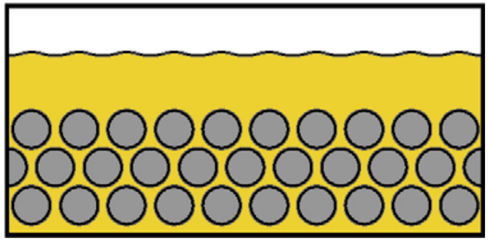
- Fiber print-through is caused by a mismatch in resin and fiber cure shrinkage, CTE, and CME properties.
    - The result is a series of ripples on the surface of the replicated optic.

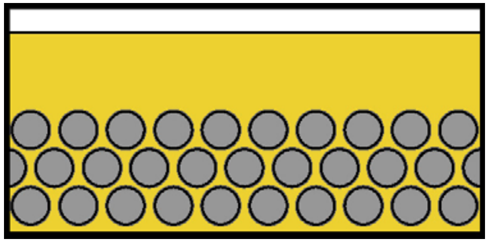


One solution to this problem is to increase the resin-rich layer thickness to damp out the effects of property mismatch.

- Unfortunately, this results in a thick layer of resin of much higher CTE than the composite substrate.



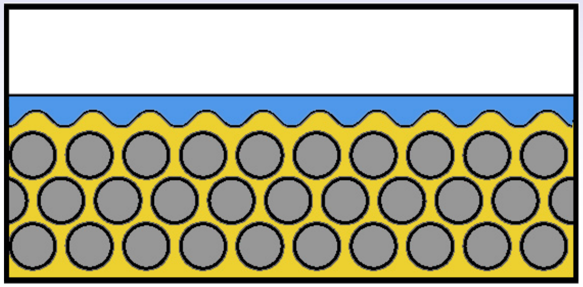




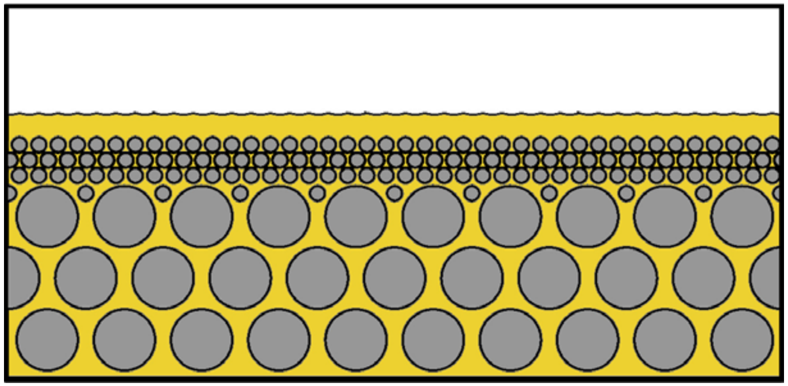
Carbon-Fiber Composites

Fiber Print Through Issue

- Another solution involves over coating the replicated optical surface with a harder material (glassy sol gel) and polishing the resulting surface. COI has shown this to be viable.
  - The harder material damps out the resin/fiber mismatch errors more effectively than a thin polymer layer.



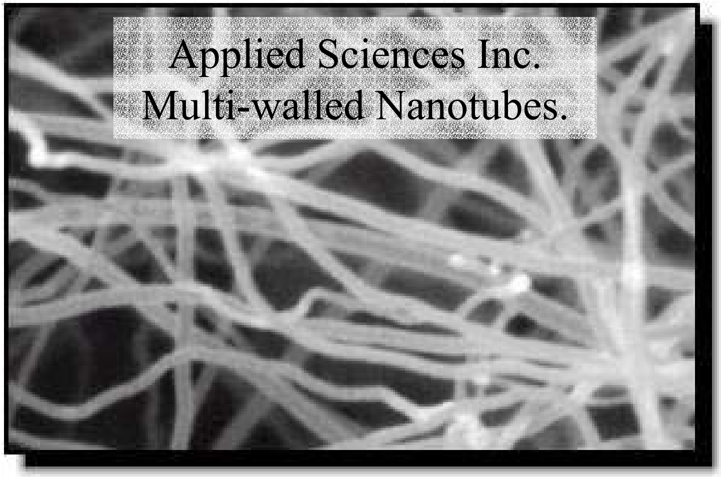
- Another solution is to applying a layer of nano-fiber reinforced polymer composite between the main composite substrate.



  - The smaller diameter fibers will cause a smaller magnitude print-through effect.

Carbon Nano Fibers

- Carbon nanotubes are a new and exciting material that could be used to make composites for mirrors.
  - Single walled nanotubes display amazing properties that are accompanied by an amazingly high price.
  - Multi-walled nanotubes also have great properties but at a reasonable cost.
    - Diameters as low as 100nm.
    - Tensile modulus of 600 GPa and strength of 7 GPa
    - CTE of –1.0 ppm/C and thermal conductivity of 1950 W/mC.

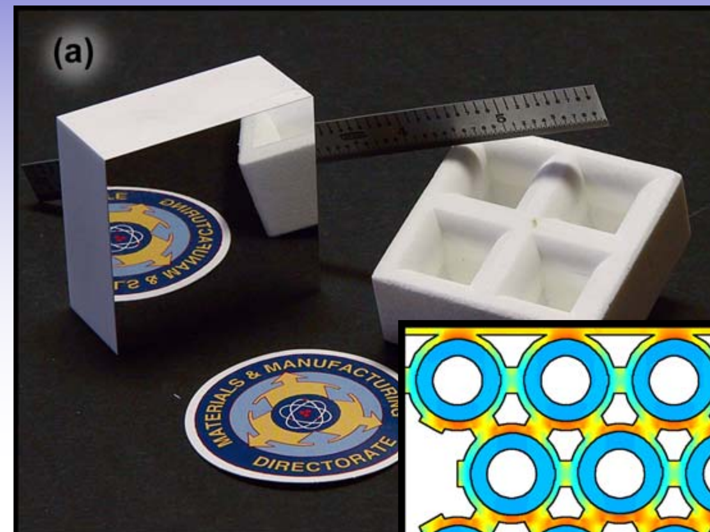


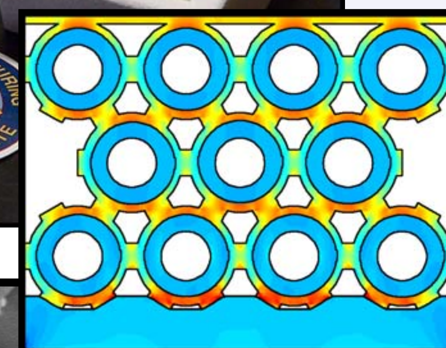
Carbon nanofiber imaged by scanning electron microscope.

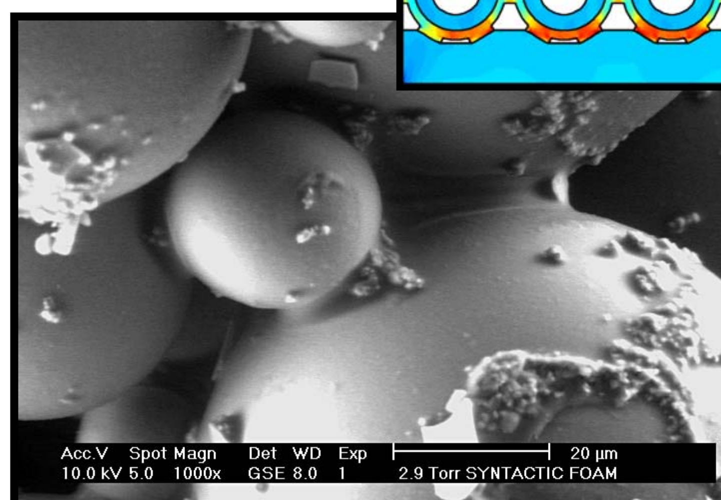
Syntactic Foam Composites

(for replicated optics)

- **AFRL IR&D with NRO Support**
- Developing syntactic foam models to predict strength and modulus as a function of the sphere size, sphere distribution, and the amount of binder. Validated with experiments.
- Investigate molding with ribs on a replicated surface.
- The figures show 2 replicated mirrors (one with molded ribs), a syntactic foam micromechanics model, and an SEM micrograph of a dry syntactic foam.





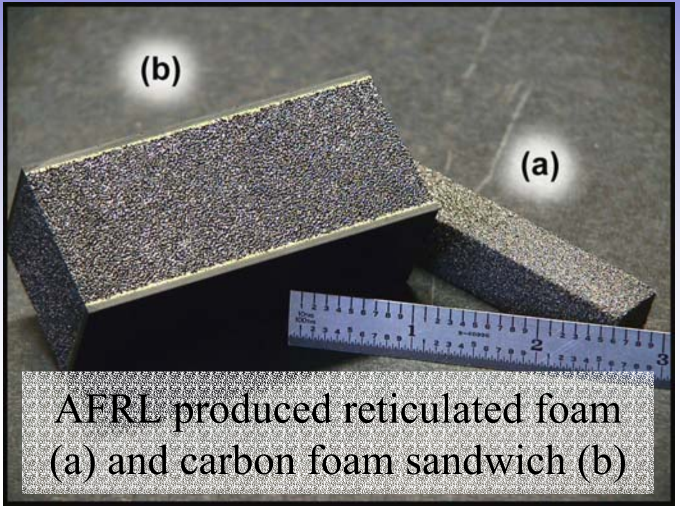


Foam Mirrors

(for mirror structural substrates and cores)

AFRL-IR&D

- Carbon foam refers to a broad class of materials that include reticulated glassy, carbon, and graphitic foams that are generally open-cell or mostly open-cell.
- They can be tailored to have low or high thermal conductivity with a low CTE and density.
- These foams have high modulus but low compression and tensile strength. Work is on-going to improve their tensile strengths.
- Fig (a & b): Carbon foam with face sheets of carbon fiber and nano-fiber reinforced polymer.
- Foams of C, Si, and SiC are being investigated by various vendors.



AFRL produced reticulated foam (a) and carbon foam sandwich (b)

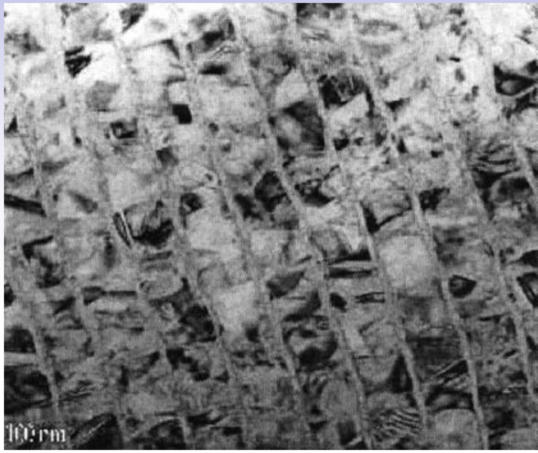

Touchstone Research Carbon Foam Mirror Blank

FY03-04 ML Mirror Portfolio
In-house R&D for the NRO Hybrid Mirror

Foil Replication and Adhesion

Objectives

•Investigate foil/nanolaminate replication and adhesion technology to eliminate or reduce polishing cost and reduce fabrication schedule for SiC mirrors.



•**Key Issues**

•The state-of-the art metallic nano laminate foils based on Cu+CuZr are produced by Lawrence Livermore NL and have a CTE = 13ppm/°K. New foil/nanolaminate chemistries need to be identified that have lower CTEs comparable to SiC and C/Mg structural substrates. Si, SiC, and Si_3N_4 based materials have CTEs in the 2 to 4 ppm/°K range.

•Methods must be developed to adhere these foils to the structural substrate without affecting the figure (20nm) and finish (1nm) tolerances of the foil.

•Foil fabrication technologies must be identified that can be scaled to meters.

•Foil and adhesive stability and degradation limits must be determined.

FY03-04 ML Mirror Portfolio

In-house R&D for the NRO Hybrid Mirror

Foil Replication and Adhesion

AFRL/ML + NRO funding supported government and on-site contractor (UES Inc.) personnel to investigate **alternate foil chemistries**

•Investigate the chemistries needed to produce a replicated foil or nanolaminate with a CTE ~ 2 to 4 ppm/ºK range.

•We are looking at:

a. SiC, CTE=3.8 ppm/ºK (20-473ºK), Density= 3.2 gm/cc
b. Si_3N_4, CTE= 0.6 ppm/ºK (70-400ºK), Density 3.8 gm/cc
c. Silicon, CTE= 2.7ppm/ºK, Density 2.33gm/cc

•Investigate various deposition methods

a. Magnetron Sputtering
b. Electron Beam Evaporation
c. Large Area Filtered Arc Deposition(LAFAD)
d. Pulse Laser Deposition

Summary & Conclusions

• We have discussed many different types of materials where CTE tailorability is used to increase modulus, strength, thermal conductivity, and toughness while decreasing CTE, density, cost and schedule.

•Small mirrors (3 inches) have been made from each of them to show proof of concept. Larger mirrors (0.5m) need to be fabricated and tested for their limits. Scaleability to 4 meters and NDE techniques needs to be investigated in the future.

•Mirrors are not the only components that need looked at. Optical benches, deployment devices (hinges and latches), lighter weight + higher stroke actuators, electronic downsizing, and large area coatings are just a few components where advanced materials are needed.

• Unfortunately, a lot of this work is being done under on shoe-string budgets. We need to come together as a community and help formulate a <u>Major US Initiative</u> focused on the development of advanced materials for large, lightweight, hybrid mirrors and optical components that will be needed for numerous application of the 21st century.

•I would like a list your needs and research suggestions to help sell this initiative.